Accepted Manuscript

Journal of the Geological Society

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DOI: https://doi.org/10.1144/jgs2019-056

Received 29 March 2019
Revised 24 June 2019
Accepted 28 June 2019

Supplementary material at https://doi.org/10.6084/m9.figshare.c.4561001

To cite this article, please follow the guidance at http://www.geolsoc.org.uk/onlinefirst#cit_journal

Where does the time go? Assessing the chronostratigraphic fidelity of sedimentary rock outcrops in the Pliocene-Pleistocene Red Crag Formation, eastern England

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ABSTRACT

It is widely understood that Earth's stratigraphic record is an incomplete record of time, but the implications that this has for interpreting sedimentary outcrop has received little attention. Here we consider how time is preserved at outcrop using the Neogene-Quaternary Red Crag Formation, England. The Red Crag Formation hosts sedimentological and ichnological proxies that can be used to assess the time taken to accumulate outcrop expressions of strata, as ancient depositional environments fluctuated between states of deposition, erosion and stasis. We use these to estimate how much time is preserved at outcrop scale and find that every outcrop provides only a vanishingly small window onto unanchored weeks to months within the 600-800 ka of 'Crag-time'. Much of the apparently missing time may be accounted for by the parts of the formation at subcrop, rather than outcrop: stratigraphic time has not been lost, but is hidden. The time-completeness of the Red Crag Formation at outcrop appears analogous to that recorded in much older rock units, implying that direct comparison between strata of all ages is valid and that perceived stratigraphic incompleteness is an

inconsequential barrier to viewing the outcrop sedimentary-stratigraphic record as a truthful chronicle of Earth history.

TIME AND OUTCROP

It has been recognised for over a century that Earth's stratigraphic record is time-incomplete, and that vertical successions of sedimentary strata are punctuated historical chronicles (Barrell, 1917; Dott, 1983). Unconformities and diastems riddle the rock record at a variety of scales (Miall, 2016) and such gaps, of often unknown extent and duration, have implications for considering strata as a record of elapsed geological time. They can skew estimates of ancient rates of sedimentation or climate change (Sadler, 1981; Miall, 2015; Kemp et al., 2015; Toby et al., 2019), can mean that allogenic signals have been shredded by autogenic processes (Jerolmack and Paola, 2010; Foreman and Straub, 2017; Hajek and Straub, 2017), and can add a further layer of incompleteness to a fossil record already rendered lacking by taphonomic filters (Kowalewski and Bambach, 2003; Holland, 2016; Saraswati, 2019). Furthermore, the overwhelming proportion of 'missing time', relative to preserved stratigraphic time, has long raised fundamental questions about the veracity of strata as a historical archive and whether they can truly represent ancient processes and environments.

A recent upsurge of developments in understanding the time-completeness of the stratigraphic record, particularly from a stratigraphic modelling perspective, is comprehensively discussed by Miall (2015) and Paola et al. (2018). Recent advances can be summarized as pointing to three recurring themes, namely: 1) Ancient strata are dominantly a record of commonplace sedimentary processes and not exceptional events (Jerolmack and Paola, 2010; Paola, 2016); 2) The time-dominant sedimentation state under which the sedimentary-stratigraphic record accumulated was stasis – that is, 'neither deposition nor erosion', rather than 'either deposition or erosion' (Tipper, 2015; Davies et al., 2017; Foreman and Straub, 2017); and 3) Any time-gaps in the deposition of one vertical stratigraphic section of basin fill can have been contemporaneous with deposition of strata elsewhere within the same depocentre (Runkel et al., 2008; Reesink et al. 2015; Gani, 2017).

These emerging understandings have potentially major implications for the way we interpret the geological record (e.g., Miall, 2014; Hampson et al., 2015; Durkin et al., 2017; Davies and Shillito, 2018; Kocurek and Day, 2018). A better understanding of time-length scales that present at rock outcrop is needed because it is common practice for geologists to focus attention at the scale of an individual outcrop or group of outcrops, which provide the most tangible point of contact for understanding the physical sedimentary records of ancient environments, and their intensive properties (e.g., palaeontological or geochemical signatures).

The purpose of this contribution is to investigate time at outcrop by describing field observations that act as proxies for time-completeness, using examples from the Neogene-Quaternary Red Crag Formation of eastern England; a sub-tidal sedimentary succession that is known from a number of discrete, small outcrops.

THE RED CRAG FORMATION

The Red Crag Formation is the second oldest unit of the late Cenozoic Crag Group, which crops out in eastern England (McMillan et al., 2011; Mathers and Hamblin, 2015; Lee et al., 2015) and consists of four discrete transgressive formations (the others, from oldest to youngest, being the Coralline Crag, Norwich Crag, and Wroxham Crag formations) (Figure 1). Each of the formations is separated by regional unconformities and all were deposited in open marine settings near the landward head of the Crag Basin, a localized embayment in the south-west corner of what is now the North Sea. Although there is some uncertainty in the

Red Crag Formation's precise age, the oldest parts of the unit are agreed to be latest Pliocene (Piacenzian) while the youngest are earliest Pleistocene (Gelasian), and the duration of Red Crag deposition is consistently reported to be between 600-800 ka (e.g., Zalaciewicz et al., 1988; Hallam and Maher, 1994; Gibbard et al., 1998; Head, 1998; Maher and Hallam, 2005; Williams et al., 2009; Wood, 2009; Wood et al., 2009; McMillan et al., 2011; Riches, 2012; Mathers and Hamblin, 2015). Additionally, it has long been recognised that the unit is diachronous and becomes older southwards (Riches, 2012); its oldest strata (an outlier at Walton-on-the-Naze, Essex) may be separated from the rest of the unit by an unconformity (e.g., Wood et al., 2009).

Lithologically, the Red Crag Formation consists of poorly-sorted, semi-consolidated, coarse-grained shelly quartz and carbonate sands which are dark green and glauconitic at depth, but which have been weathered to an iron-stained orange-red colour at outcrop (Humphreys and Balson, 1985; McMillan et al., 2011). The sediment usually has an extremely high content of aragonitic and calcitic shell debris, although at some locations the upper part of the unit has been decalcified to pure quartz sand as a result of later Pleistocene soil development (Kendall and Clegg, 2001). Variable palaeocurrent indicators, large-scale cross-bedding, bioturbation, and sedimentary structures including flaser bedding and bidirectional cross-strata indicate that the unit was primarily deposited by migrating large-scale subtidal sandwaves (Figures 2-3) (Dixon, 1979, 2005, 2011, Mathers and Zalasiewicz, 1988, Zalasiewicz et al., 1988, Balson et al., 1991, Hamblin et al., 1997).

Outcrops of the Red Crag Formation

Outcrops of the Red Crag Formation are typically of limited extent, but of good quality for discerning its internal sedimentary architecture (Figure 4). No individual outcrop approaches the full 40 metre thickness of the unit, but this can be ascertained from some of the hundreds of boreholes that have been made across unexposed parts of the regional outcrop belt (Figure 5; British Geological Survey, 2018). Two primary types of exposed outcrop exist and have formed the focus of this study: 1) Crag pits (six outcrops; Figure 4A), which are static inland exposures formerly quarried for agricultural and aggregate purposes (O'Connor and Ford, 2001); and 2) Coastal outcrops (two outcrops; Figure 4B-C), which comprise dynamic natural exposures of small cliffs, that are frequently reworked by wave activity along a highly erodible and recessive coastline (Environment Agency, 2015).

Significantly for later discussion in this paper, the vertical cliff faces exposed in both types of outcrop are of limited extent: crag pits have a mean height and lateral extent of 5.5 metres and 93.5 metres respectively, while coastal outcrops have equivalent dimensions of 9 metres and 1555 metres.

Further details of the regional geology and specific information on outcrops is available as a supplementary file to this paper.

SEDIMENTATION STATES AND THE PRESERVATION OF TIME

The sedimentary-stratigraphic record has long been considered to be an archive of elapsed time: simplistically, deposited sediment 'preserves time' and erosion of that sediment 'removes time'. A time interval is generally considered preserved when a sedimentary deposit representing any time from that interval remains in the stratigraphic column at the location of interest (Strauss and Sadler, 1989; Paola et al., 2018). However, this definition of preserved time is complicated by the recognition that not all time at a given location would have equated to a period of deposition or erosion; in fact, many sedimentary systems will have existed in a condition of sedimentary stasis for the majority of the time they were active (Dott, 1983; Tipper, 2015; Foreman and Straub, 2017; Paola et al., 2018).

Tipper (2015) has suggested that time spent in stasis cannot be preserved because there is nothing to be preserved. Yet while this may be conceptually true for understanding how synthetic vertical stratigraphic columns record time, it is unsatisfactory for explaining real-world sedimentary rock outcrops. If a sedimentary surface, persisting for a duration of sedimentary stasis in an active environment, is not eroded, then that surface has the potential to accrue information generated by processes and events occurring as time passes during the stasis interval: for example as multiple generations of surficial ichnological, microbial, and abiotic sedimentary structures, or distinct geochemical or pedological vertical profiles (Miall and Arush, 2001; Barnett and Wright, 2008; Christ et al., 2011; Davies et al., 2017; Davies and Shillito, 2018; Paola et al., 2018; Shillito and Davies, 2019). Where such signatures can be identified alongside signatures of erosion and deposition, it becomes possible to broadly estimate the duration of accrual of a package of sedimentary strata as preserved at a given outcrop, with implications for how representative that outcrop may be of ancient sedimentary environment.

Stratigraphic signatures of sedimentation states in the Red Crag at outcrop

Time spent in different sedimentation states is recorded in different ways in the sedimentary-stratigraphic signatures of the Red Crag Formation at outcrop. By definition, the most obviously recorded sedimentation state is deposition: without deposition there is no sediment accumulation, and so time spent in this state is recorded as the sediment pile itself. Likewise, erosion has left discernible stratal discordances within the sediment pile, which are readily apparent as bounding surfaces (Figure 6). Erosional surfaces are primarily a negative record of time, recording the erasure of time records that once existed (Sadler, 1999). Within the Red Crag Formation, none of the studied outcrops contain major erosional surfaces (i.e., extending the full width of an exposure), so there is little direct evidence of wholesale deletion of depositional records at outcrop scale (Figure 6).

Sedimentary stasis is revealed in the Red Crag Formation as bounding surfaces that record a synoptic topography from the time of deposition (Paola et al., 2018). These can sometimes be recognised by the preservation of complete bedforms with convex top surfaces, often with evidence that later sediment was draped over the antecedent substrate morphology (Figure 7).

More commonly, the extensive Red Crag ichnofauna (Figure 3, Table 1) gives clues to sedimentary stasis. Every burrowed horizon in the unit provides evidence that intervals of stasis punctuated the deposition of the Red Crag Formation, because the colonization of a substrate requires time for organisms to excavate sediment without disturbance from erosion or deposition (Goldring, 1960; Buck, 1985; Frey and Goldring, 1992; Pollard et al., 1993; Davies and Shillito, 2018). As complete vertical burrows may be impossible to distinguish from truncated burrows without bedding plane evidence (e.g., Hallam and Swett, 1966; Goldring, 1960; Buck, 1985; Wetzel and Aigner, 1990; Nara, 1997; Davies et al., 2009) (lacking in the unconsolidated Red Crag Formation), burrows can only be determined to be complete when they intersect with synoptic topographies (e.g., inclined burrows intersecting with foresets/ dune lee slopes: Figure 8; Pollard et al., 1993). However, even where they are only preserved in truncated form, they are direct evidence that deposition was not continuous, and instead alternated with a state of stasis (+/- erosion) (Figure 8).

Sedimentation states cannot be maintained in perpetuity so, at any given location, states of deposition (D), erosion (E) and stasis (S) will be in spatial and temporal flux while the sedimentation system is active. Compound sedimentation states reflect this variability (i.e., D-E-D, D-S-E-D, D-S-D and D-E-S-D) and can be deduced by close scrutiny of signatures that mark the transition between two strata, which by definition must each record deposition (D). Such signatures of compound sedimentation states are common and highly variable within the Red Crag Formation (Figure 9), as a direct result of their depositional environment and the narrow frame of reference provided by outcrop.

Why are signatures of compound sedimentation states common and variable in Red Crag outcrops?

Tipper (2015) introduced the concept of 'point sedimentation systems' to explain time-completeness in vertical synthetic stratigraphic columns: referring to a specific point (in a mathematical sense) within the space of a sedimentary environment, variably subject to erosion, deposition and stasis. For the purpose of studying real-world strata, this concept can be practically extended to be applicable to the narrow spatial focus offered by all or part of an outcrop, which provides a sedimentary record of a 'point' within a much wider sedimentary environment, across which stasis, erosion and deposition can be happening simultaneously (Runkel et al., 2008; Davies and Shillito, 2018). Within a depositional environment, the spatial frame occupied by a future outcrop could witness multiple compound sedimentation states over the time that it took to accrue vertically, resulting in high variability in signatures of compound sedimentation states. This variability is particularly pronounced in the Red Crag Formation, because it was deposited in a tidal setting, where intervals of deposition and erosion are very often punctuated by stasis. For example, in modern shallow tidal sediments, Reineck (1960) calculated that $< 0.0001\%$ of geological time was recorded as deposited sediment layers at any given point. Intertidal settings experience frequent stasis: following tidal stillstand (of as little as 10-20 minutes duration) an interval of erosion (or further stasis, if the reversed current is weak) can generate pause planes within bedforms (Boersma, 1969; Boersma and Terwindt, 1981; Allen et al., 1994). Subtidal sandwaves are also variable: at any spatial point on the seafloor, a substrate may aggrade, degrade or remain in stasis over short timescales, even while the underlying sandwave remains in a net migratory state. In a survey of 25 very large dunes at 26-30 metres water-depth in the modern North Sea, Van Dijk and Kleinhans (2005) monitored the change in elevation of the sea floor substrate over the course of a year. They found that 8 sampling locations (all on the upper lee slope of dunes) saw a decrease in elevation (i.e., experienced erosion), 33 saw an increase in elevation (i.e., experienced deposition), but that 6 saw no change in elevation (i.e., stasis).

Estimating the duration of sedimentation states

Red Crag Formation outcrops are amalgams of signatures of different sedimentation states and compound sedimentation states. By estimating how long each recorded sedimentation state lasted, it is possible to estimate the time it took to accrue the sedimentary strata that constitute a particular outcrop.

Deposition

Many Red Crag outcrops record the deposits of sandwaves, which, in modern tidal settings, can migrate a distance equivalent to their average height within a single tidal cycle of c. 12 hours (Dalrymple, 1984). The average height of ancient Red Crag sand waves is not directly discernible due to erosional truncation and limited outcrop size. However, the minimum height (i.e., the vertical distance between the top and bottom of a foreset) of different bedforms is calculable. For the largest cross-bedded units known, the rate of migration was likely in excess of 3 metres every 12 hours, meaning that the time taken to deposit the layer that extends for half the width of the present outcrop (Figure 4A) would have been at most 15 days.

Tipper (2016) suggested that herringbone cross-strata was another sedimentary structure that could be used to constrain instantaneous sedimentation rates, illustrating this by suggesting that such bidirectional cosets are deposited during one flood-ebb tidal cycle. This is flawed because there is no guarantee that such opposite-directed cross-strata were deposited during the same single semi-diurnal cycle (Kvale, 2012): deposition and erosion may occur only during stronger tides, and substrates may be stasic for considerable intervals of a tidal year (Allen et al., 1994). However, the bidirectionality seen in the Red Crag Formation does imply that the agents of deposition (i.e., flood and ebb tidal currents) could feasibly have deposited paired sets over intervals of hours to months (e.g., see examples in Figures 2B, 2C and 8C).

Erosion

While stratigraphic time lost to erosion may be unknowable, the duration of erosive events can be estimated. Certain erosional surfaces in the Red Crag Formation appear to be intrinsically linked to tidal timescales – for example, internal erosional surfaces within cosets of cross-bedding (Figure 10) most likely reflect erosional pause planes (Boersma and Terwindt, 1981). Like reversing cross-strata, the frequency of repetition of these could be semi-diurnal or longer term, but the duration of erosion for individual surfaces would have been accommodated within one tidal reversal (i.e., an interval of hours).

Stasis

We know very little about time represented by ordinary surfaces with no signs of stasis (Dott, 1983). As these are typically the most common surfaces, it is only possible to estimate the minimum duration of stasis for an outcrop succession. In the Red Crag Formation, this is enabled by the consideration of burrowed surfaces. The burrowing rate of different individual tracemakers in modern shallow marine settings has received only limited attention (Dafoe et al., 2006; Gingras et al., 2008), but a selection of quantified rates are shown in Table 1. These can be used to estimate the minimum time that the system was in stasis, by calculating how long it would take for the fastest-burrowing potential tracemaker to excavate the largest burrow along a given stasis-surface, where the internal volume of the burrows can be roughly approximated as one or more cylinders ($\pi r^2 h$, where r is burrow radius and h is burrow length).

The time taken to excavate particular individuals of the known ichnogenera (Table 2) provides a very approximate and conservative minimum estimate of the time spent in stasis.

The most important conclusion here is that burrow formation is a geologically-rapid process that occurs only during sedimentary stasis, but there a number of caveats to these estimates, namely 1) it is impossible to unravel the temporal sequence of the generation of a suite of individual burrows along the same stasic surface; 2) the speed at which burrows are excavated depends on factors such as grain size; 3) estimates are made with reference to the limited data published on burrowing rates, and 4) very large dwelling burrows (e.g., *Psilonichnus*) are problematic because stasis is most likely to have persisted for an unknown interval after the burrow was excavated, and while the tracemakers were continuing to use the burrows as domiciles. Burrowing rates of modern crabs (the suspected *Psilonichnus*-tracemakers (Balson and Humphreys, 1987)) have only been calculated as the time taken for an individual to fully bury their carapace in sediment (e.g., McLay and Osborne, 1985; Lastra et al., 2002), and estimates of excavation rates at depth (where overburden and compressive force chains of packed grains impede burrowing speed (Dorgan et al., 2006)) are not reported. As an approximation of excavation speed for the largest *Psilonichnus*, we here use the maximum invertebrate rate reported in Table 1 of 10 cm^3/hr, although the margins of error here may be large.

Time taken to deposit individual outcrops of the Red Crag Formation

Precisely determining the time taken to deposit an individual outcrop of the Red Crag Formation is impeded by 1) the inability to accurately determine sequences of events during stasis from their physical records, 2) the inability to confidently calculate original dune height from preserved foresets, and 3) a reliance on potentially imperfect modern analogues. Despite this, the lack of major erosional surfaces at outcrop suggests that little time has been destroyed and lost at outcrop-scale and is instead missing due to stasis. Equally, that time spent in stasis appears to have been relatively short because there is a lack of complete bioturbation reworking of primary sedimentary structures or shell material, and no evidence for palimpsesting of multiple generations of burrows at the same horizon, despite the Red Crag seas supporting an abundant infauna. The lack of evidence for prolonged bioturbation implies that horizons were likely in stasis on timescales no longer than hours to days (Table 2), and probably reflect tidal current quiescence on semi-diurnal or synodic timeframes (Kvale, 2012).

Figures 10 and 11 show how the entire sediment piles that comprise pit outcrops of the Red Crag Formation can reasonably be estimated to have accumulated over time intervals of days to months. Thus, when we encounter the unit as an individual outcrop, we are dealing with sediment accrued over very minor time intervals, well within the range of human experience. This observation seems counterintuitive when we consider that the time taken to deposit the Red Crag Formation, as an entire stratigraphic entity, was 600-800 ka, equating to average sedimentation rates of 0.5-0.66 cm/ka to deposit the units full 40 metre thickness. However, as noted by Miall (2015), such quantified average sedimentation rates are essentially meaningless: it is an understanding of the instantaneous sedimentation rate (taken to deposit a particular bedform or sedimentary component), which informs most on the nature of deposition. The small spatial scale of the Red Crag Formation outcrops has discretized the time-length scale of visible strata to focus only on those features deposited over sub-annual sedimentation rate scales (Miall, 2015).

WHERE DOES THE TIME GO? DISCUSSION

As every individual outcrop of the Red Crag Formation reveals only a maximum of a few months in the life of the active sedimentary environment, they provide vanishingly small windows into the 600-800 ka of total ‘Crag-time’. Two obvious questions arise from this understanding: 1) Where did the vast majority of Crag-time end up, if not preserved at outcrop? and 2) If we have such small windows, how can we trust them to be representative of what was really happening during Crag-time?

With respect to the first question, part of the answer lies in the time-length scale of the exposed outcrops that we are viewing: the window on time that we have is miniscule, but so is the window on space. For example, the outcrop at Capel Green (Figure 10) may reveal as little as 35 days out of 292 million days (800 ka) of Crag-time – but then the spatial area of the outcrop is only 156 m^2 out of approximately > 4 billion m^2 of Crag Group (as mapped onshore). When we consider that stratigraphic time is smeared laterally over an outcrop belt (Runkel et al., 2008; Reesink et al. 2015; Gani, 2017; Davies & Shillito, 2018), the null hypothesis is that it is highly improbable that any two outcrops record the exact same time interval: they are all floating pockets of preserved time with no hope of being accurately chronostratigraphically anchored within the 600-800 ka boundaries of net Crag-time (Figure 12). This opens the possibility that the fraction of preserved Crag-time may not be negligible after all: we simply cannot access the majority of the mapping unit as it is concealed as subcrop. In other words, time is not lost, but hidden. We can only see strata from the vantages of outcrop or core, but these are tiny windows relative to the bulk volume of sediment that is still preserved today (e.g., Figure 5). It is simply impossible to see all of the internalized physical strata hidden behind cliff faces and between outcrop exposures or cores. We contend that those ancient sedimentary products that can be witnessed today do not record *temporally* rare events, but rather that the observable outcrop exposure of sedimentary product is a *spatially* rare phenomenon: relative to the extent of (a) the ancient depositional environment and (b) the full extent of its unexposed lithostratigraphic corollaries.

The outcrops of the Red Crag record exposures of 'days', but are they representative of 'every day' process during the interval of deposition? The null hypothesis must be that they are, because of the strong similarity between the different exposed outcrops, which all contain a comparable array of tidal sedimentary structures and trace fossils (Figures 2-3). This attests to the likelihood that mundane, non-unique conditions were persistent for most of Crag-time (i.e., the 'strange ordinariness' discussed by Paola et al., 2018). Exposed outcrops are random samples of the net volume of a succession: if they are all telling the same story, despite having been deposited on month-timescales that are separated by unknowable intervals of time, then it is highly probable that they are preserving the 'norm' rather than exceptions.

The bias of the present

A present-to-past vantage point can skew and bias our perspective of a variety of geological phenomena (e.g., Budd and Mann, 2018), and this is particularly true when considering the Red Crag Formation from a time perspective: a relatively young formation, with relatively transient outcrops (i.e., due to coastal retreat). In this regard, the active reworking of coastal outcrops is informative, and sheds light on the *remanie* fossils that are common throughout the Crag Group as a whole.

Remanie fossils are those which are reworked from significantly older deposits and end up forming a fraction of a population of much younger fossils within a given stratum (Craig & Hallam, 1963; Kowalewski & Bambach, 2003) and are common within the Red Crag Formation (Riches, 2012). However, *remanie* assemblages of Red Crag fossil fauna are also presently being formed as cliff collapse along the Suffolk coast mixes Pliocene-Quaternary sediment and fossils into modern beach sands (Environment Agency, 2015): complete shells of the distinct, left-handed gastropod *Neptunea contraria* are commonly found in loose sediment of beaches such as Bawdsey (Figure 13), but are definitively reworked from the Red Crag Formation as the modern range of this species is much further south (Bay of Biscay to Morocco) (Nelson & Pain, 1986). Once on the beach, many of the reworked fossil shells re-enter circulation as sedimentary particles and, if fortuitously buried with sand, could – like recent shell debris – have thousand-year plus longevity within the active beach environment (e.g., Flessa, 1993). Significantly, the environments into which these future *remanie* fossils and their host sediment are being eroded are extant nearshore and shallow marine environments (Figure 14), with direct analogy to the ancient crag environments. This appears to be the latest stage in a historical continuity of fossil-recycling between crag units: the Red Crag contains reworked shelly fossils from the Pliocene Coralline Crag, and the Norwich and Wroxham crags contains reworked shelly fossils from the Plio-Pleistocene Red and Coralline crags. If the Red Crag Formation is presently being reworked into extant crag-like environments, this begs the question: are we still living in Crag-time?

We propose a perspective where the present coastline is considered to be the boundary of an active 'North Sea Crag' (Figure 15), stacked on top of the extent of the depositional environments of the previous crags. Each of the older units is separated by an unconformity that marks intermittent disruption in the continuity of shallow marine deposition: in the case of the unconformity between the most recent crag (Wroxham) and the present, this is associated with glacioeustatic relative sea-level fall. The unconformities, corresponding to the Group 2 unconformities (10^4–10^5 years) of Miall (2016), only reflect retreat of crag deposition away from our present-biased frame of reference (i.e., the onshore outcrop belt), and offshore parts of the North Sea will have seen continuous deposition throughout some of the unconformity intervals. As such, the received perspective that we are now "post-crag" may be a bias from living in the present, and onshore, and could be no different from the apparent post-crag conditions that would have been perceived had we been undertaking geological investigations on land during the interval of unconformity generation between, say, the Red and Norwich crags. The extensive, inter-formation unconformities are distinguished from the intensive, intra-formation discontinuities (e.g., Figure 6) because: 1) their trigger was external to the depositional system (e.g., sea-level change rather than autogenic recyling of sediment piles within a sedimentary environment); and 2) they diminish time-completeness regionally, while intensive unconformities remain most important in diminishing time-completeness within individual outcrops.

One marked difference between the interval between the Wroxham Crag and today (compared with the unconformity intervals bounding the Red Crag), is that sediments that post-date the Wroxham Crag Formation currently exist onshore: most notably the 0.4 Ma Anglian glacial deposits (Lee et al., 2015). However, a large fraction of the Crag Group outcrop belt has negligible or patchy cover from younger sediments, so a future rise in relative sea-level could theoretically transplant subtidal sandwave deposits immediately on top of similar facies of the ancient crag formations. The extensive erosional unconformity separating the ‘future crag’ from the ancient crag would, in many places, be indistinguishable in its character from the preceding unconformities that separate the formations of the Crag Group (although would potentially be marked in places with spatially restricted alluvial and glacial ‘members’).

Implications for the preservation of time in older formations

The notion that crag deposition may be a work in progress is speculative but geologically rational, and has implications time-preservation in older strata. The duration of crag deposition, whether finished or not, corresponds to the persistence or persistent reappearance of marine conditions in the south-western North Sea region over the last c. 5 Ma (Lee et al., 2018): an interval of time inferior to the duration of many stratigraphic formations in the geological record. Significantly, the sedimentological characteristics of the Red Crag Formation which show its outcrops were deposited on human timescales are also common in much more ancient strata, deposited in similar sedimentary environments (Figure 16).

Lithified ancient strata may differ from the crag through forming much thicker successions (formed over longer intervals, in tectonic settings more prone to subsidence), and sometimes being exposed at vertical scales in which extensive unconformities are more apparent, but fundamentally they are comprised of similar building blocks, with potentially similar spatial extent of outcrop and time significance, to the Red Crag Formation.

This understanding shifts how we understand the chronostratigraphic fidelity of ancient strata. Ager (1986) ended a paper concerning the time significance of a 10 metre-thick debris flow deposit in Jurassic strata with the conclusion that "it all happened one Tuesday afternoon". Notwithstanding that Ager's (1986) sentiment has been widely disputed (e.g., Fletcher et al., 1986; Sheppard, 2006), in the Red Crag Formation it seems more likely that any individual outcrop all happened one "February going into March" – a subtle but key difference revealing strata not as dramatic events, but sediment piles deposited both quickly and unexceptionally. This removes a level of perceived incompleteness from the ancient record and suggests that any given outcrop is most likely representative of normal conditions, particularly when similar facies signatures are replicated in multiple discrete outcrops of the same unit.

This 'bias towards the boring' in preserved strata means that we can trust the fidelity of the signatures within such outcrops more than is commonly perceived. The intensive properties of even Precambrian strata at outcrop should be just as time-complete as the Red Crag Formation at outcrop: any outcrop can still be a monthly or sub-annual record which is unanchored, within a given time frame (Figure 17). The implication of this is that, if we bracket Earth's sedimentary record by geological period, the first appearance (followed by persistence thereafter) of sedimentary or ichnological (or, in some instance, palaeontological) features at a number of worldwide outcrops, probably reflects genuine evolutionary origin, and cannot be dismissed as being unreliable due to the "incompleteness of the sedimentary record".

CONCLUSIONS

Observing the Red Crag Formation from a temporal perspective supports recent understanding of strata and time and attests that stasis was the dominant sedimentation state, ordinariness is the dominant signature, and Crag-time is smeared laterally across exposed and unexposed parts of the Red Crag outcrop belt.

Outcrops of the Red Crag Formation are discrete pockets of sediment that was deposited on monthly to subannual timescales, related to the tidal rhythms of its depositional environment. The duration of outcrop accrual can be estimated with sedimentological and ichnological proxies for rates of deposition, erosion and sedimentary stasis. These reveal that miniscule fractions of elapsed geological time can be seen at outcrop (relative to the 600-800 ka duration of deposition of the formation), but this is only because outcrops provide windows onto miniscule areas of space (relative to the area of original deposition). We suggest that outcrops of sedimentary strata of any age are directly comparable, recording mundane, sub-annual-timescale, sedimentation. In other words, although the rock record is unavoidably incomplete, when it is viewed at outcrop and considered from a time perspective it can be seen to be intricately detailed, surprisingly high-resolution, and, in many instances, there may be no reason to doubt its veracity as a historical chronicle.

ACKNOWLEDGEMENTS

APS was supported by the Natural Environment Research Council (grant number NE/L002507/1). This paper was improved by useful reviews from Andrew Miall and Liam Herringshaw, and comments from editor Adrian Hartley.

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LIST OF FIGURES

Figure 1 – Stratigraphic context and regional outcrop extent of the Crag Group, with detailed geological maps showing selected study sites and the local extent of Red Crag Formation exposure (BC: Bawdsey cliffs; BK: Buckanay Farm; BM: Boyton Marshes; CG: Capel Green; CH: Chillesford; NF: Neutral Farm; NZ: Walton-on-the-Naze; SH: Shottisham). Note that ages on stratigraphic column are approximate and maximum thicknesses are from borehole data only. Individual Crag Group formations considered to have internal unconformities. No outcrop exists where a full transect through the known stratigraphy occurs.

Figure 2 – Selected sedimentary characteristics of the Red Crag Formation. A) Heterolithic wavy tidal bedding: muddy horizons record deposition during tidal stillstands. Boyton Marshes. Visible part of ruler is 90 cm. B) Small-scale reversing cross-stratification. Palaeoflow shown for sets highlighted in red and green (depiction of palaeocurrent direction after Davies et al., 2018). Shottisham. Scale bar is 10 cm. C) Large-scale reversing cross-stratification. Palaeoflow shown for sets highlighted in red and green (depiction of palaeocurrent direction after Davies et al., 2018). Neutral Farm. Person is 185 cm. D) Reworked phosphatic pebbles (e.g., within circled area) within shell-rich lithofacies. Buckanay Farm. Scale bar is 10 cm. E) Typical shell-rich lithology predominantly composed of variably-complete shelly fragments of bivalves and gastropods. Buckanay Farm. Scale bar is 10 cm. F) Decalcified quartz rich lithology at top of exposed Red Crag Formation, exhibiting evidence of cryoturbation. Walton-on-the-Naze. Scale bar is 10 cm.

Figure 3 – Trace fossils of the Red Crag Formation. A) *Cylindrichnus* isp. Buckanay Farm. Visible ruler is 20 cm. B) *Diopatrichnus* isp. Capel Green. Scale bar is 10 cm. C)

Macaronichnnus segregatis Buckanay Farm. Visible ruler is 20 cm. D) Detail of *M. segregatis*. Boyton Marshes. Scale bar is 1 cm. E) *Polykladichnus irregularis*. Capel Green. Scale bar is 10 cm. F) *Psilonichnus upsilon*. Note large form – example in yellow box is 120 cm long. Boyton Marshes. Visible ruler is 80 cm. G) *Skolithos linearis*. Shottisham. Scale bar is 10 cm. H) *Teichichnus rectus*. Walton-on-the-Naze. Scale bar is 10 cm. I) *Thalassinoides isp*. Walton-on-the-Naze. Scale bar is 10 cm.

Figure 4 – Outcrop style of the Red Crag Formation. A) Largest crag pit visited in this study: Buckanay Farm, exposing c. 8 metres of vertical section over an area of c. 200 m^2. B) Coastal outcrop near Bawdsey Manor (south end of Bawdsey cliffs). 10 metre-high cliffs which are no longer retreating due to sea defences, and are increasingly overgrown with vegetation. C) Coastal outcrop near East Lane (north end of Bawdsey cliffs). Dynamic coastline with c. 5 metre-high cliffs. Photograph was taken in January 2014; since when (at the time of the most recent visit, October 2018) there has been c. 3 metres of cliff retreat in places, and beach sediment has built up to a height of 3 metres in front of the cliff face.

Figure 5 – Stratigraphic cross-section of eastern Suffolk, showing the limited spatial extent of Crag Group knowable from core and outcrop, relative to its inferred abundance at depth. Thickness of Crag varies due to underlying topography and later incision/erosion. Location of outcrops is approximate relative to line of section (BC: Bawdsey cliffs; BK: Buckanay Farm; SH: Shotisham; CG: Capel Green; NF: Neutral Farm; BM: Boyton Marshes). Core data used to construct section from British Geological Survey (2018a). Cores shown are: 1: TM34SW21; 2: TMSW20; 3: TM34SW23; 4: TM24SW19; 5: TM34SW18; 6: TM34SW17; 7: TM34NW24; 8: TM34NE11A; 9: TM34NE16; 10: TM34NE20; 11: TM34NE23; 12 TM35SE75. Point A is located at 51°59’41.1”N, 01°24’51.2”E; Point B is located at 52°04’04.9”N, 01°25’16.2”E; Point C is located at 52°07’04.8”N, 01°24’53.6”E.

Figure 6 – Erosional surfaces (shown in pink) indicating where previously recorded time has been erased (identified by discordance of laminae), and acting as bounding surfaces between sedimentary records of deposition. Note the small scale of these features: they are instances of intensive erosional diastems, rather than regional (or even outcrop-wide) unconformities. A) Largest erosional surface visible in any of the visited crag outcrops – concave scoured base to large cross-bedded dune set. Buckanay Farm. Scale bar is 2 metres. B) Concave scoured base to smaller bedform. In this instance the erosional surface truncates a horizon (shown in blue) which has been colonized by *Polykladichnus* trace-makers. The order of sedimentation states here was thus: 1. Deposition (below blue horizon); 2. Stasis (colonization of blue horizon); 3. Deposition (above blue horizon); 4. Erosion (partial erasure of stages 1-3); 5. Deposition (above pink horizon). Boyton Marshes. Scale bar is 50 cm. C) Planar erosional surface representing levelling of earlier dune tops. Boyton Marshes. Metre-stick for scale.

Figure 7 – Synoptic topography at different scales within the Red Crag Formation and indicative of true substrates/chronostratigraphic surfaces. A-B) Cross-sectional view of undulating bedforms, possibly generated during aggradational conditions under supercritical flow. Surfaces highlighted blue preserve the instantaneous topography from the time of deposition (pink line highlights erosional surface). Boyton Marshes. Person is 170 cm. C-E) Synoptic topography of small bedforms, shown in blue – white area in C is enlarged in E. Some horizons appear to preserve original bedform morphology, supported by their colonization by *Cylindrichnus* with preserved ‘trumpet’ form at top (t), suggestive of proximity to original apertural opening on the seafloor (Hallam and Swett, 1966; Davies et al., 2009). Horizons shown in black are more ambiguous. Additionally, there may have been some minor reworking of the bedform crests during tidal reversals, suggested by superimposed, reversed ripple cross-lamination (r). Scale bar is 20 cm. Boyton Marshes.

Figure 8 – Trace fossils as indicators of sedimentary stasis. A-B) Multiple horizons of *Cylindrichnus* burrows (shown in different colours) attesting to non-steady sedimentation. At least seven episodes of stasis (+/- erosion) during the interval taken to deposit this 70 cm package of sediment. Walton-on-the-Naze. Metre stick for scale. C-D) Intervals of stasis that were followed by intervals of erosion are seen where incomplete *Cylindrichnus* burrows terminate against constructed erosional boundaries (shown in pink). In contrast, some cross-strata foresets can be seen to be colonized by apparently complete *Cylindrichnus*, oriented relative to the dipping foreset (blue). These imply that the tracemaker constructed their burrow relative to the inclined substrate and that some of the foresets themselves are synoptic topographies (Pollard et al., 1993). In other words, these dunes were not in continual motion and there were intervals where the dune lee slope persisted as a true substrate and could be colonized – such irregular motion of dunes is not uncommon in tidal settings (e.g., Allen et al., 1994). Capel Green. Scale bar is 1 metre.

Figure 9 – Signatures of compound sedimentation states recorded in the Red Crag Formation. A) Sand deposition (D1), followed by heterolithic wavy tidal bedding – lithology arising from fluctuations of deposition and stasis (i.e., tidal stillstand) (Ds2). Subsequently, these layers have been partially eroded; however, erosion was discontinuous and followed by a short interval of stasis which has preserved the aspect of the collapsing wavy bedding (Es3), subsequently interred as the sedimentation state reverted to deposition (D4). Capel Green. Visible part of ruler is 80 cm. B) *Cylindrichnus* burrow within heterolithic wavy tidal bedding (see Figure 2A for location). During intervals of stasis, tracemaker thickens its burrow (S), but after interval of deposition (D) adjusts to newly elevated seafloor, resulting in pinching and thickening of burrow within heterolithic sediment (Nara, 1997). Boyton Marshes. Pen is 14 cm long. C) Cross-bedding with *Macaronichnus* burrows along individual foresets (e.g., along light blue lines), attesting to punctuated dune migration. Dune top has

subsequently been truncated by erosion (dark blue line), but this was followed by a more prolonged interval of stasis, attested to by the denser abundance of *Macaronichnus* along the horizontal erosional plane. The neglible tiering of *Macaronichnus*, and horizontal distribution, indicates that these were emplaced during post-erosional stasis and are not contemporaneous with the less dense, diagonally-oriented, examples along the foresets. Buckanay Farm. Ruler is 20 cm long. D) Example of deposition and erosion with no evidence for intervals of stasis. Erosional surface (pink) is followed by bedforms climbing at an angle of 10-15°. These record a continuous state of deposition (at a high rate of sedimentation), but one which is intrinsically linked to the erosion of bedforms (i.e., reworking of migration ripple trains): hence the resultant stratigraphy is dominated by constructed boundaries rather than synoptic topography. Boyton Marshes. Visible part of ruler is 1 metre long.

Figure 10 – Outcrop at Capel Green, showing surfaces arising from erosion and stasis and estimated duration of formation (scale bar is 2 metres). Approximate minimum time to deposit complete package of sediment visible in yellow box was c. 35 days (828 hours of deposition and stasis, plus unknown time lost to erosion). Order of Events: 1. Ss1 (201 hours); 2. Dp1 (120 hours, including at least 6 increments of instantaneous stasis); 3. Es1 (unknown missing time); 4. Dp2 (108 hours, including Ss2-4 [9 hours each] and at least 6 increments of instantaneous stasis); 5. Es2 (unknown missing time); 6. Dp3 (64 hours, including Ss5 [9 hours] and at least 15 increments of instantaneous stasis); 7. Es3 (unknown missing time); 8. Ss6 (9 hours); 9. Dp4 (not estimated, limited architectural evidence); 10. Ss7 (326 hours). Duration of stasis surfaces (Ss) and depositional packages (Dp) are gauged as follows (unburrowed foresets are not numbered, and are assumed to represent instantaneous stasis time intervals at minimum). Time estimated only for those packages fully exposed in the cliff face (i.e., no consideration is given to strata at the top or bottom of the outcrop where exposure is obscured or truncated and elapsed time cannot be confidently

estimated). Ss1: *Polykladichnus* burrows: Maximum Dimensions: approximate volume 100.5 cm^3 (maximum length 32 cm (i.e., 16 cm long U-shape) maximum width 2 cm); Excavation time: 201 hours (likely polychaete tracemaker, maximum burrowing rate of 0.5 cm^3 per hour). Ss2-6: *Diopatrichnus* burrows: Maximum Dimensions: approximate volume 18 cm^3 (maximum length 10 cm, maximum width 1.5 cm); Excavation time: 9 hours (possible crustacean tracemaker, maximum burrowing rate of 2 cm^3 per hour). Ss7: *Cylindrichnus* burrows: Maximum Dimensions: approximate volume 163 cm^3 (maximum length 13 cm, maximum width 4 cm); Excavation time: 326 hours (likely polychaete tracemaker, maximum burrowing rate of 0.5 cm^3 per hour). Dp1: Minimum sand wave height: 100 cm. Lateral extent: 10 metres (at 100 cm per 12 hours): 120 hours. Dp2: Minimum sand wave height: 75 cm. Lateral extent: 675 cm. Time to migrate (at 75 cm per 12 hours): 108 hours. Dp3: Minimum sand wave height: 75 cm. Lateral extent: 400 cm. Time to migrate (at 75 cm per 12 hours): 64 hours.

Figure 11 – Outcrop at Walton-on-the-Naze, showing surfaces arising from erosion and stasis and estimated duration of formation. Approximate minimum time to deposit complete package of sediment within the field of view was c. 53 days (1264 hours of deposition and stasis, plus unknown time lost to erosion). Order of Events: 1. Dp1 (60 hours, including multiple instances of instantaneous stasis); 2. Es1 (unknown missing time); 3. Dp2 (uncertain, but possibly within one tidal reversal – see ripple lamination at base [i.e., 6 hours]); 4. Dp3 (95 hours, including multiple instants of instantaneous stasis plus Ss1-9 [1 hour each]); 5. Es2 (unknown missing time); 6. Dp4 (16 hours including multiple instants of instantaneous stasis); 7. Es3/Ss10 (uncertain order as not clear if burrows truncated or not; uncertain missing time; 509 hours of stasis); 8. Dp5 (not estimated, limited architectural evidence); 9. Ss11 (288 hours); 10. Dp6 (290 hours including Ss12-19 [1 hour each]). Duration of stasis surfaces (Ss) and depositional packages (Dp) are gauged as follows

(unburrowed foresets are not numbered, and are assumed to represent instantaneous stasis time intervals at minimum). Time estimated only for those packages fully exposed in the cliff face (i.e., no consideration is given to strata at the top or bottom of the outcrop where exposure is obscured or truncated and elapsed time cannot be confidently estimated). Ss1-9: *Skolithos* burrows: Maximum Dimensions: approximate volume 1.5 cm^3 (maximum length 8 cm, maximum width 0.5 cm); Excavation time: 1 hour (possible polychaete tracemaker, maximum burrowing rate of 0.5 cm^3 per hour). Ss10: *Psilonichnus* burrows: Maximum Dimensions: approximate volume 2545 cm^3 (maximum length 40 cm, maximum width 9 cm); Excavation time: 509 hours (likely crustacean tracemaker, maximum burrowing rate uncertain, but maximum rate of organisms in Table 1, 5 cm^3 per hour, used). Ss11: *Cylindrichnus* burrows: Maximum Dimensions: approximate volume 144 cm^3 (maximum length 15 cm, maximum width 2.5 cm); Excavation time: 288 hours (possible polychaete tracemaker, maximum burrowing rate of 0.5 cm^3 per hour). Ss12-19: *Skolithos* burrows: Maximum Dimensions: approximate volume 1.5 cm^3 (maximum length 8 cm, maximum width 0.5 cm); Excavation time: 1 hour (possible polychaete tracemaker, maximum burrowing rate of 0.5 cm^3 per hour). Dp1: Minimum sand wave height: 70 cm. Lateral extent: 380 cm (at 70 cm per 12 hours): 60 hours. Dp2: No clear stasis surfaces, but direction of ripple laminae suggests a flow reversal, possibly placing this within one 6 hour tidal reversal. Dp3. Minimum sand wave height: 60 cm. Lateral extent: 430 cm (at 60 cm per 12 hours): 86 hours. Dp4. Minimum sand wave height: 60 cm. Lateral extent: 82 cm (at 60 cm per 12 hours): 16 hours. Dp6. Minimum sand wave height: 20 cm. Lateral extent: 470 cm: 282 hours.

Figure 12 – Conceptual diagrams showing how outcrop and stratigraphy relate to the time interval of their formation, during which interval the sedimentation state variously existed in a state of deposition, erosion or stasis. A) Regional lithostratigraphy (left) considers the Red

Crag Formation to be a <40 metre thick unit, deposited over 600-800 ka during the Pliocene-Pleistocene, with the oldest strata at the bottom and youngest at the top. The possible dominant sedimentation state during the interval of Red Crag deposition (“Crag time”) is shown on the right: the oldest Red Crag deposits are at Walton-on-the Naze, in the south – as these were being deposited, there is no evidence of any deposition further north, which implies erosion (i.e., constant reworking) or stasis to the north at the onset of Crag time. By the time the depocentre had shifted to the north at the end of Crag time, no new sediment was being deposited in the south – however, as it was also not being eroded (as it can be seen today), the dominant state in the south was stasis. The 600-800 ka of Crag time is thus not vertically-stacked (as in the classic lithostratigraphic viewpoint), but rather distributed unevenly across the region. B) Block representing the Red Crag Formation as a <40 metre unit across the region (top), with areas of exposed outcrop highlighted in yellow. Below; this apparently contiguous outcrop and subcrop considered from a chronostratigraphic standpoint – any cell in the region could have experienced erosion, deposition or stasis during Crag time, but the final sedimentation state at any location (relative to what has become preserved) must have been deposition or stasis and not erosion. The cartoon shows that, although exposed outcrops are all of the same formation, at approximately the same height, they are an amalgamation of random, very rarely contemporaneous, pockets of time. C) Block representing an individual outcrop with internal bounding surfaces. Many of the surfaces reflect an interval of stasis with no time added or destroyed – however, prolonged interval of erosion has removed some of the previous time record of deposition.

Figure 13 – Modern gastropod shell (left) and *remanie* shell of Pliocene left-handed gastropod *Neptunea contraria* (right) found within modern beach sediment at Bawdsey.

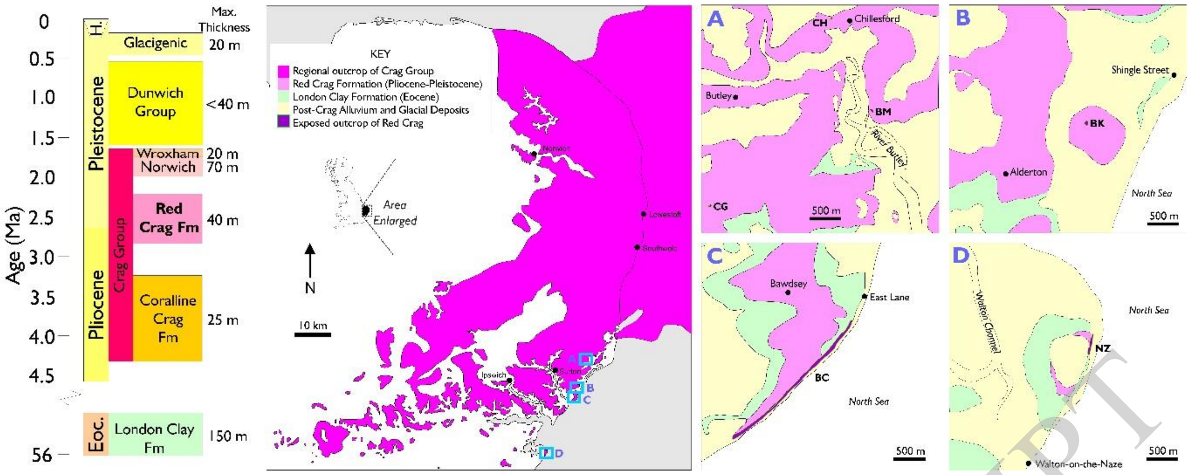
Figure 14 – Outcrop and subcrop extent of the Red Crag Formation near Bawdsey, showing how much Red Crag sediment is still subject to erosion, deposition and stasis. Only ‘islands’

of Red Crag have been preserved and recent erosion has largely stripped down to Eocene London Clay strata. At three different sites (A-C), the dominant sedimentation state and balance between deposition, erosion and stasis was different over long time intervals; (i) during Crag time, (ii) during the remainder of the Quaternary, and (iii) at the present day. At present, Crag sediment in inland crag pits is in a state of stasis. However, active erosion of Crag sediment from coastal localities is re-entraining sediment and fossils, which is being transported offshore and deposited within modern subtidal sedimentary environments that are highly similar to the ancient Red Crag subtidal sedimentary environments.

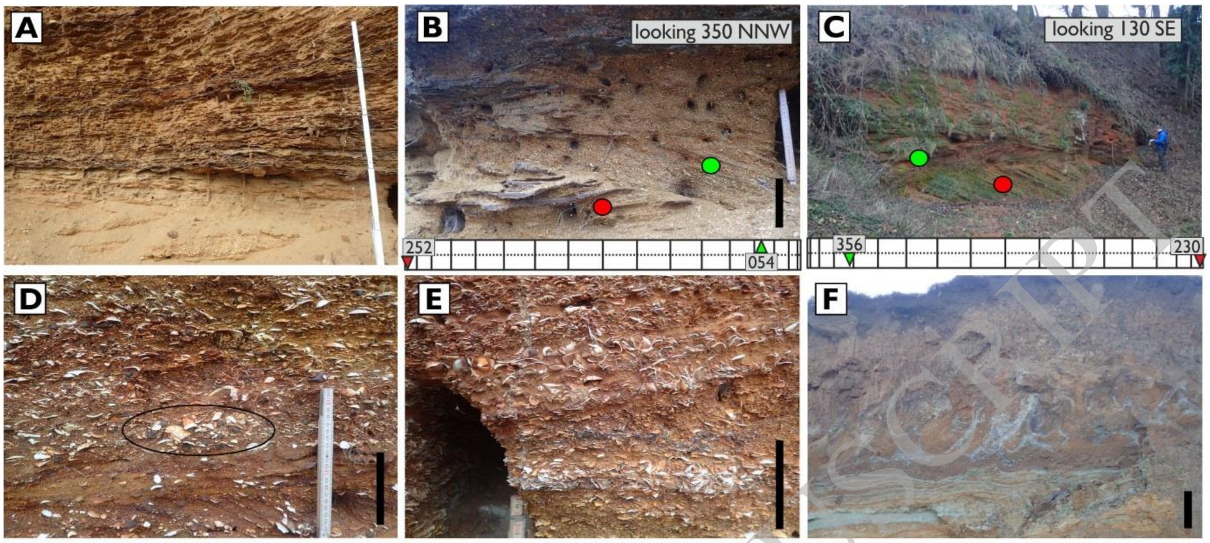
Figure 15 – The Crag Group as an 'unfinished' geological unit. Limit of active subtidal sedimentary systems for the Red Crag (RC), Norwich Crag (NC), Wroxham Crag (WC) and "North Sea Crag" ("NSC"). "North Sea Crag" refers to the subtidal sandwave sedimentary environments, presently active within the open marine North Sea, which are physically similar to the ancient crag environments, and which could feasibly be considered to be the same and potentially indistinguishable geological unit, if these strata were preserved millions of years in the future. Area shaded yellow is the region that has never experience crag deposition.

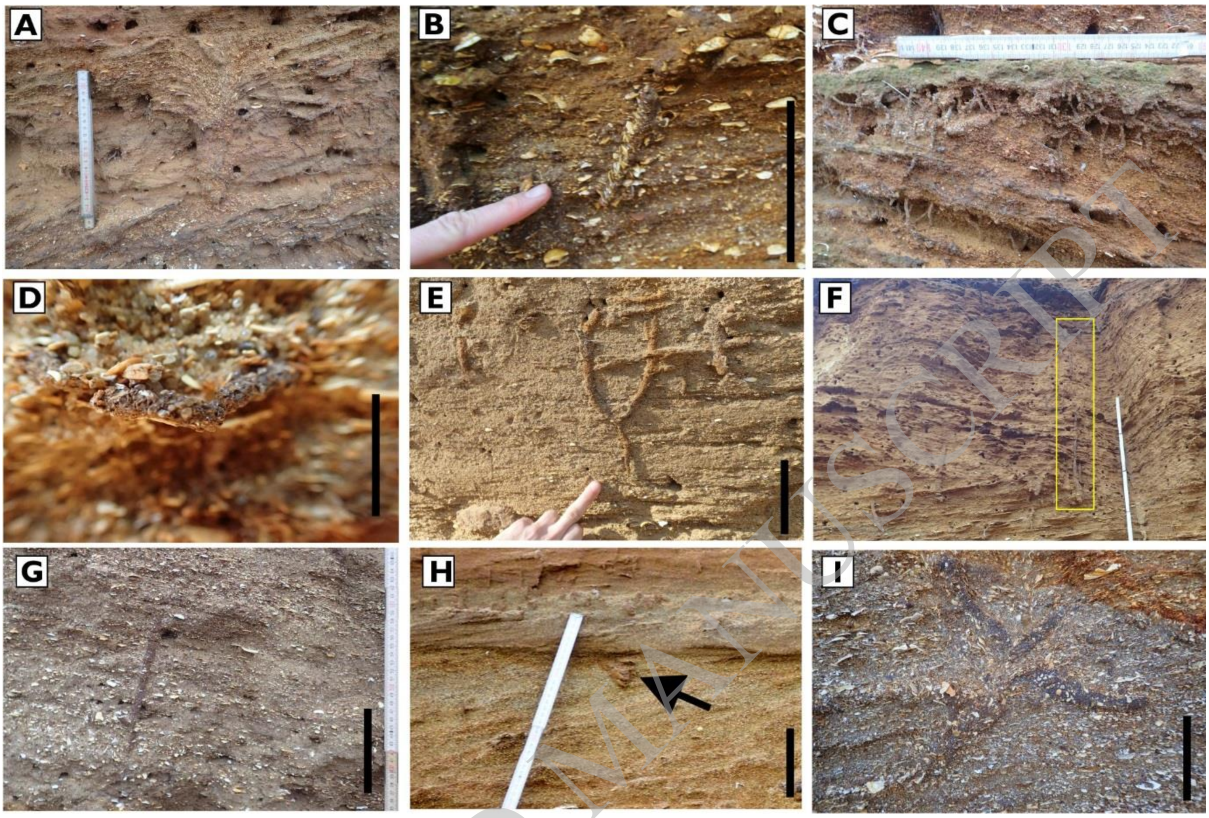
Figure 16 – Comparison of Red Crag signatures with older subtidal strata. A) Erosive-based cross-bedding at Buckanay Farm, sitting within horizontally-laminated burrowed sands. B) Erosive-based cross-bedding sitting within horizontally-laminated burrowed sands within the Silurian Tumblagooda Sandstone, Kalbarri, Western Australia. Both images shown at same scale. Note that the Red Crag is approximately 2.6 Ma and the Tumblagooda Sandstone is approximately 425 Ma, yet at outcrop scale both reveal similar sedimentary facies that would have been deposited over month(s) timescales.

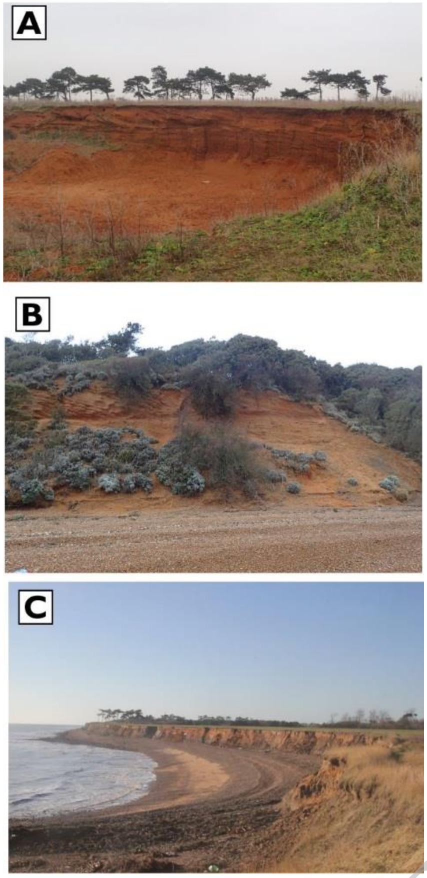
Figure 17 – Tidal signatures in the Paleoproterozoic (c. 1.7 Ga) Baraboo Quartzite, Devil's Lake, Wisconsin, United States. Despite their far greater antiquity, the timescales of formation of these features are directly analogous to similar features in the Red Crag Formation, and presently-exposed outcrops are equally unanchored pockets of human timescales within the interval of Baraboo deposition. A) Approximately 15 packages of small dune cross-strata, each reflecting migration rates in days to weeks. B) Reversing cross-strata, each set of which must have been deposited on a timescale of no more than weeks. C) True substrate recording instantaneous conditions of current ripples preserved as synoptic topography.

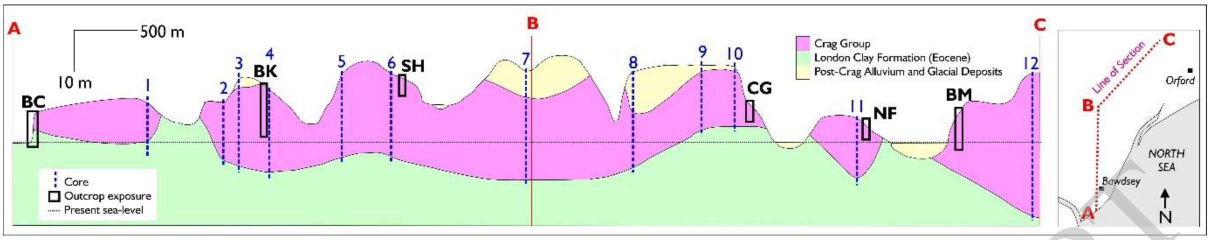


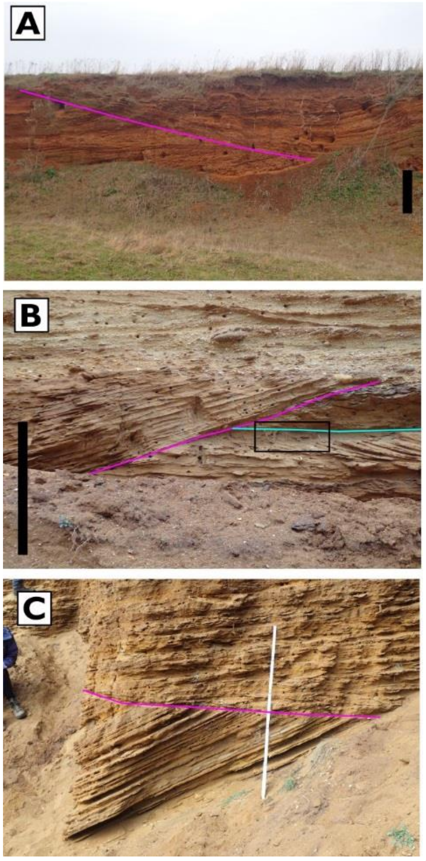
Age (Ma)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
56
H.
Pleistocene
Pliocene
Eoc.
Crag Group
Glacigenic
Dunwich Group
Wroxham
Norwich
Red Crag Fm
Coralline Crag Fm
London Clay Fm
Max. Thickness
20 m
<40 m
20 m
70 m
40 m
25 m
150 m
KEY
Regional outcrop of Crag Group
Red Crag Formation (Pliocene-Pleistocene)
London Clay Formation (Eocene)
Post-Crag Alluvium and Glacial Deposits
Exposed outcrop of Red Crag
Area Enlarged
N
10 km
Lowestoft
Southwold
Ipswich
A
B
C
D
CH
Chillesford
Butley
BM
River Butley
CG
500 m
Shingle Street
BK
Alderton
North Sea
Bawdsey
East Lane
BC
Walton Channel
NZ
Walton-on-the-Naze

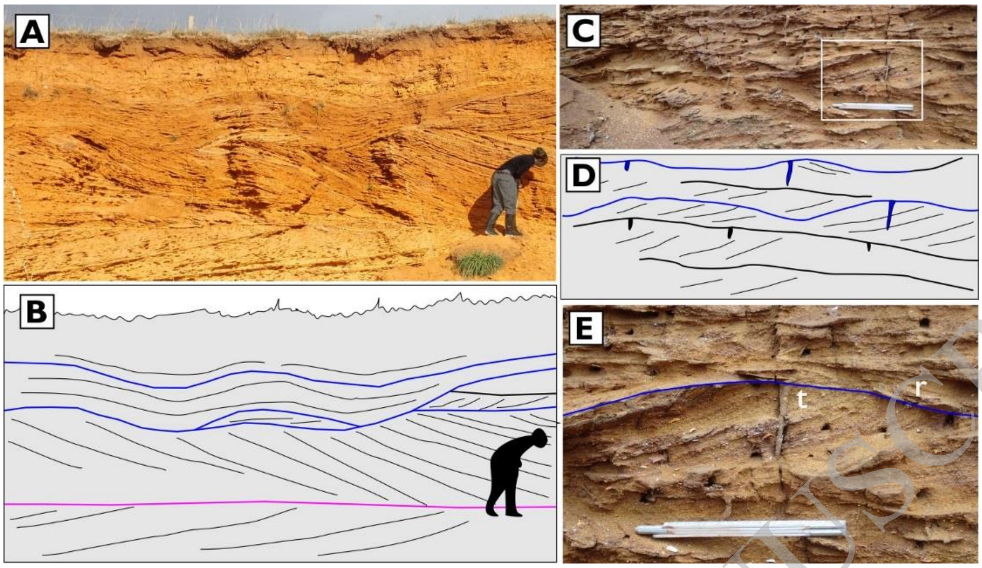

A
B
looking 350 NNW
252
054
C
looking 130 SE
356
230
D
E
F

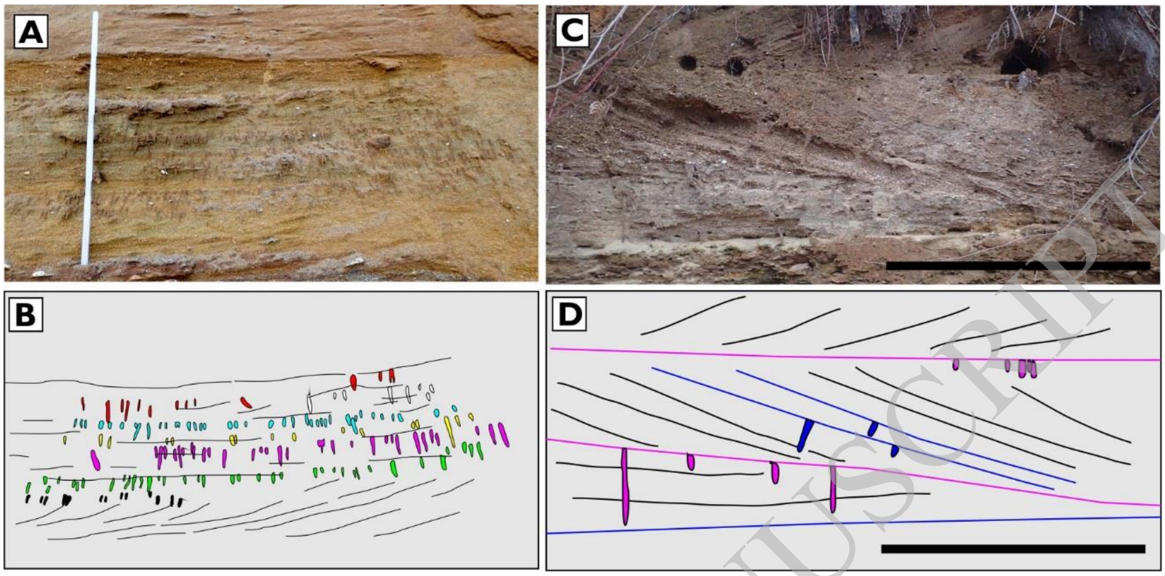

A
B
C
D
E
F
G
H
I

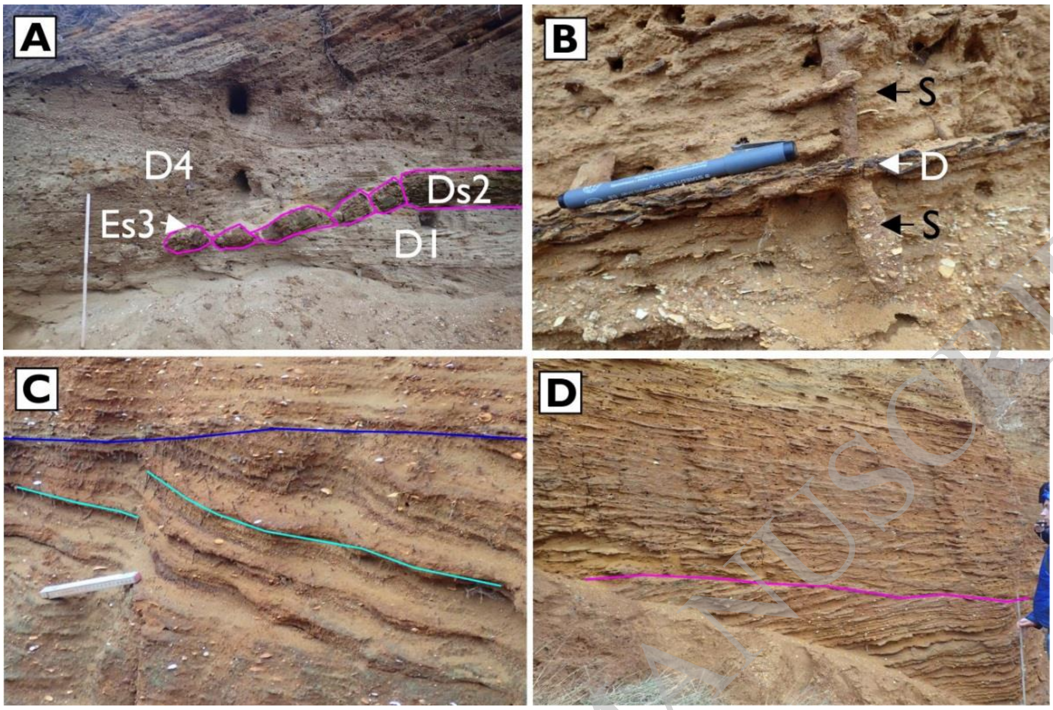

A
B
C

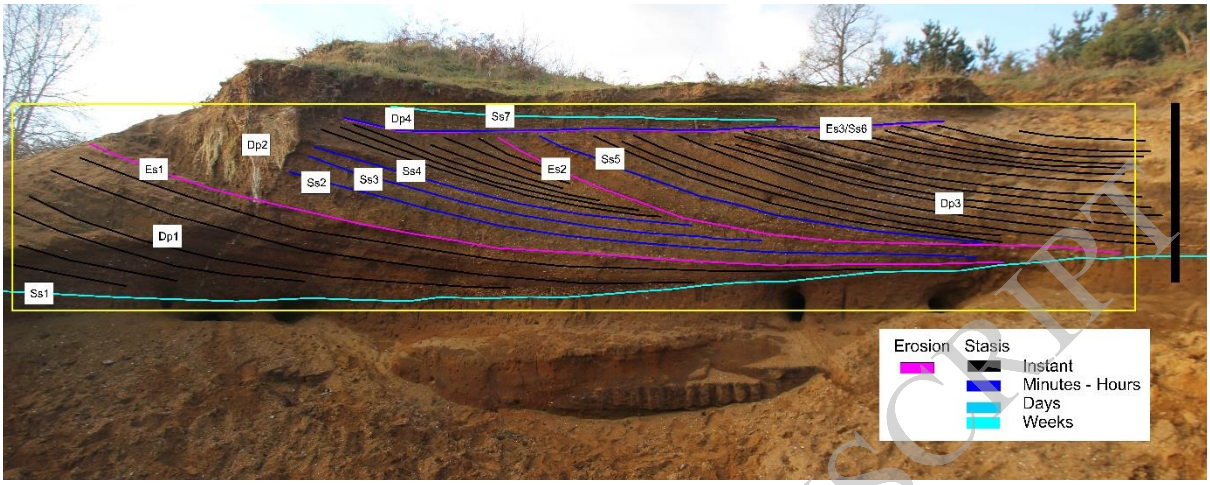

A
B
C
500 m
10 m
Crag Group
London Clay Formation (Eocene)
Post-Crag Alluvium and Glacial Deposits
BC
1
2
3
4
BK
5
6
SH
7
8
9
10
CG
11
NF
BM
12
Core
Outcrop exposure
Present sea-level
Line of Section
Orford
NORTH SEA
Bawdsey
N

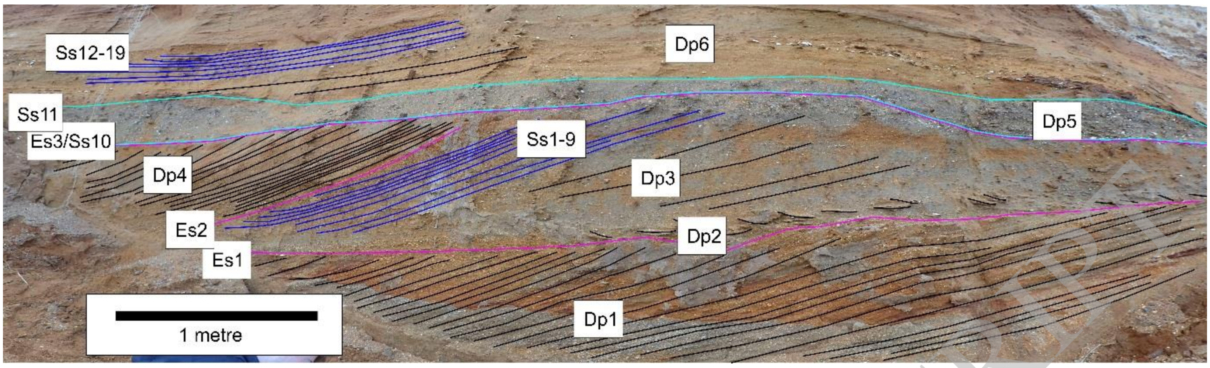

A
B
C

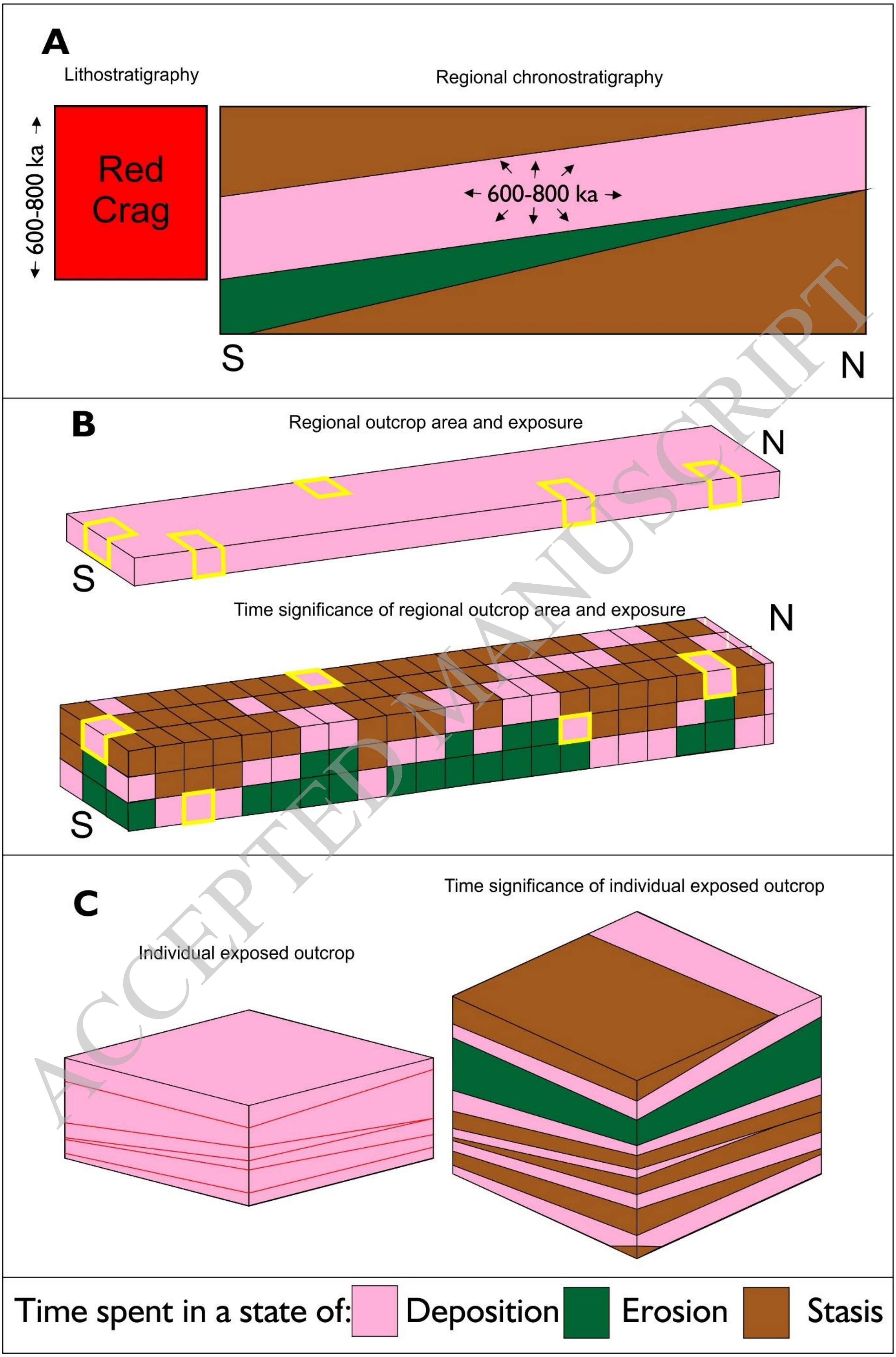

A
B
C
D
E
t
r

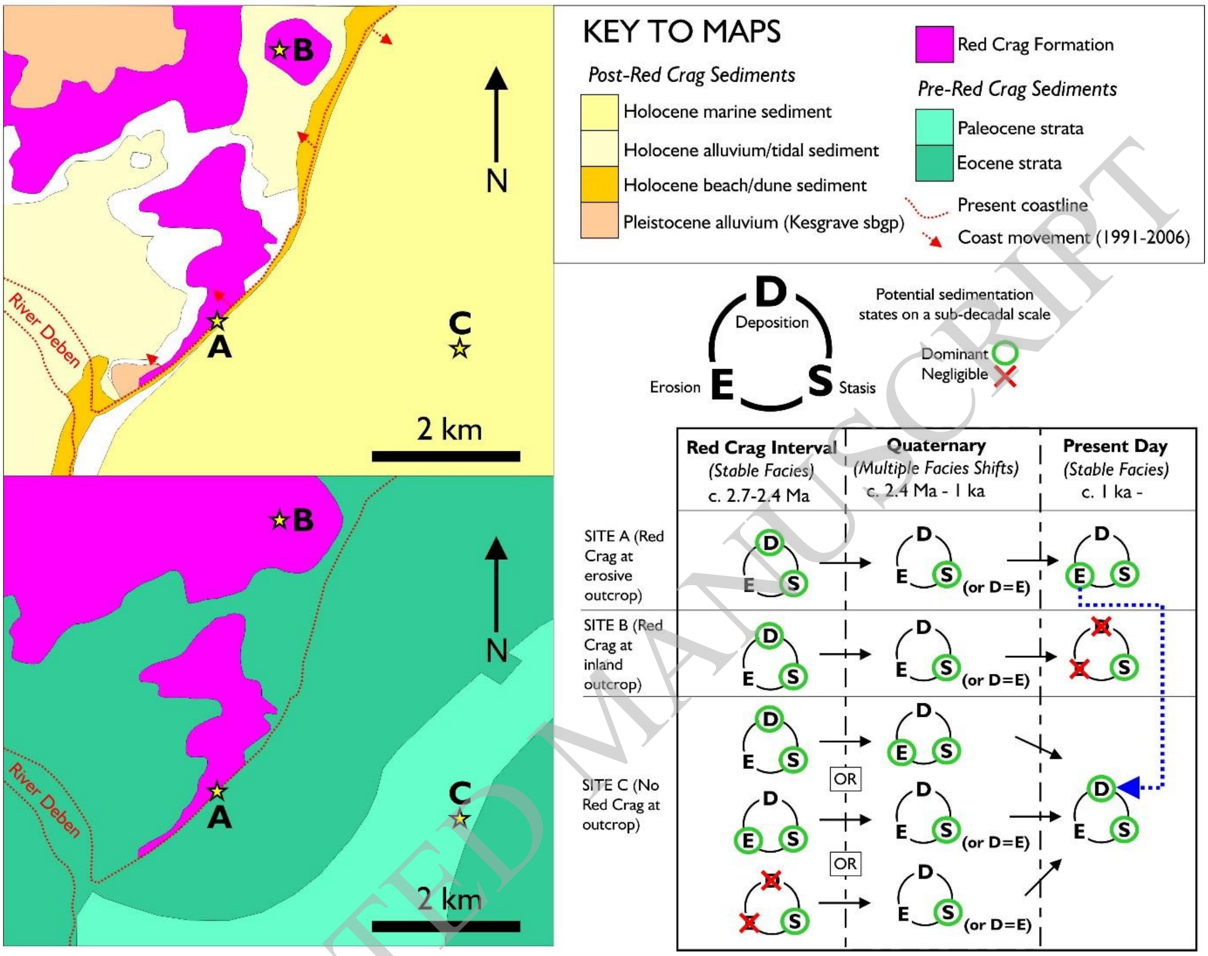

A
B
C
D

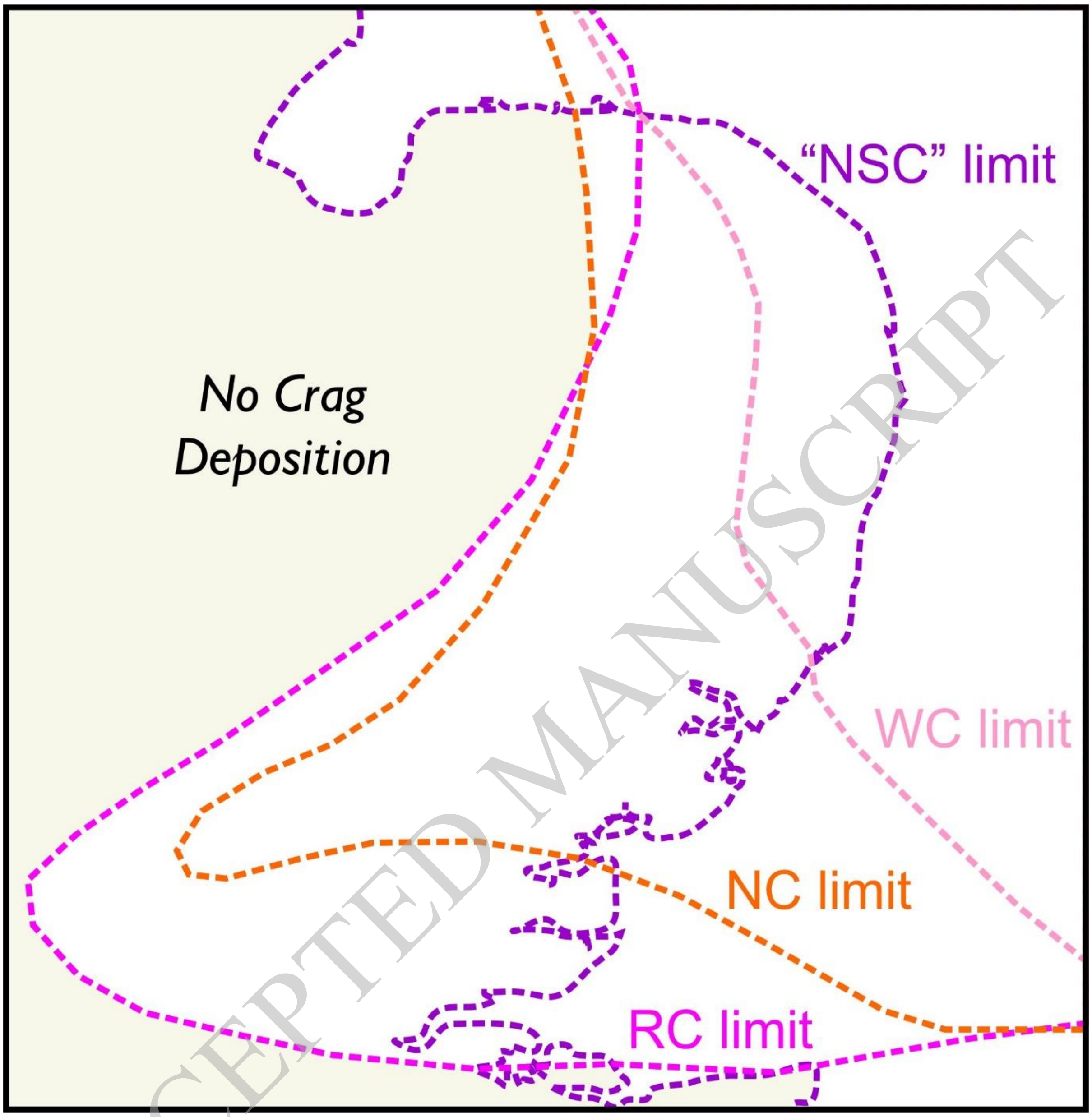

A
D4
Es3
Ds2
D1
B
S
D
S
C
D

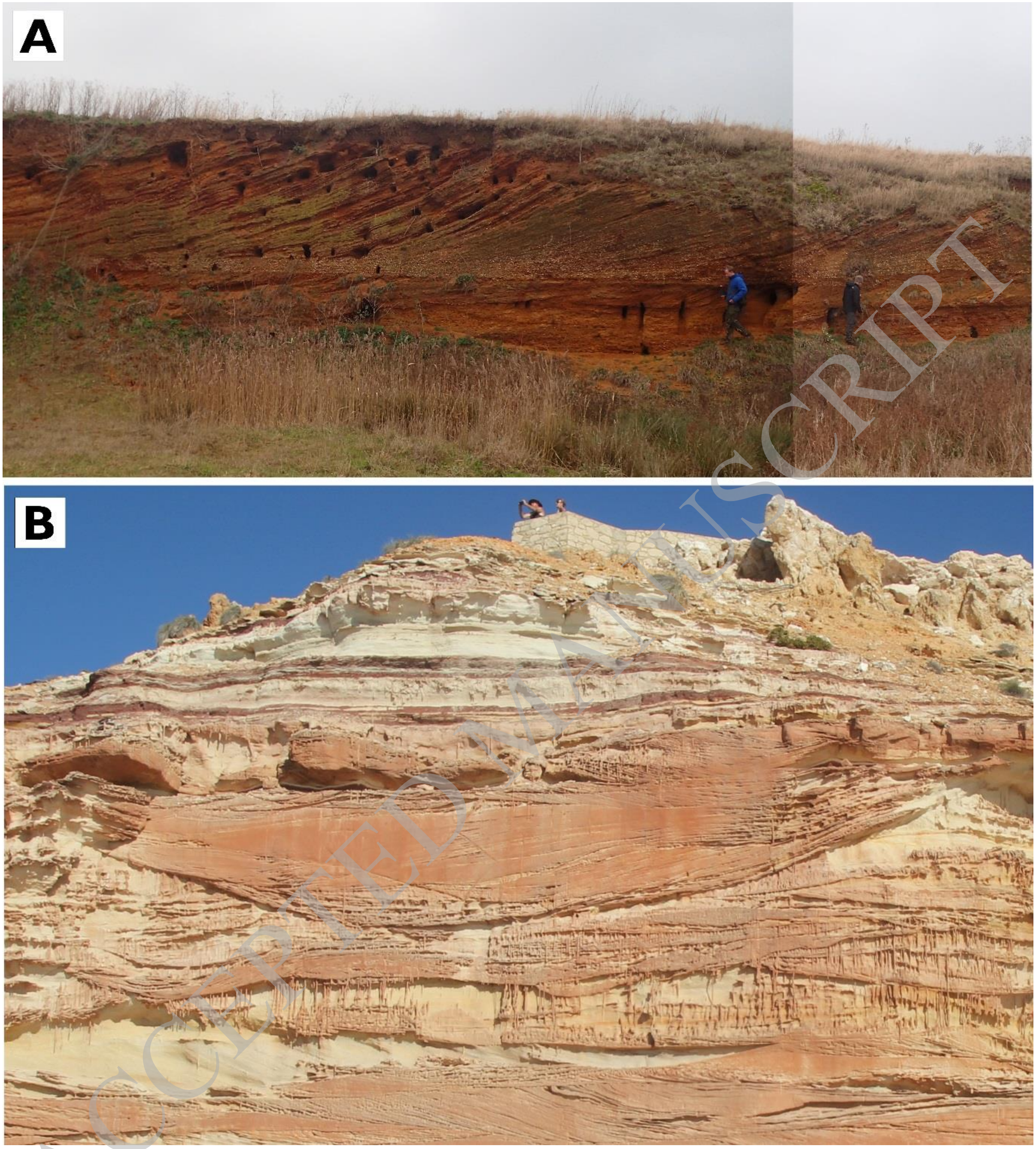

Dp4
Ss7
Es3/Ss6
Dp2
Es1
Ss2
Ss3
Ss4
Es2
Ss5
Dp3
Dp1
Ss1
Erosion
Stasis
Instant
Minutes - Hours
Days
Weeks

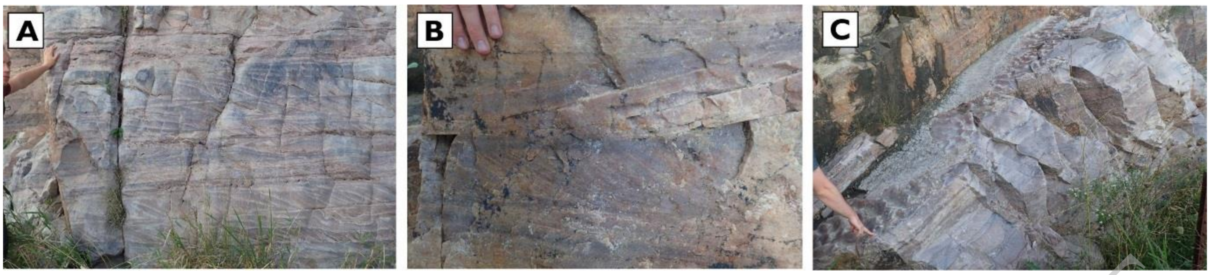

Ss12-19
Dp6
Ss11
Es3/Ss10
Ss1-9
Dp5
Dp4
Dp3
Es2
Dp2
Es1
Dp1
1 metre


A
Lithostratigraphy
Regional chronostratigraphy
600-800 ka
Red Crag
600-800 ka
S
N
B
Regional outcrop area and exposure
N
S
Time significance of regional outcrop area and exposure
N
S
C
Time significance of individual exposed outcrop
Individual exposed outcrop
Time spent in a state of:
Deposition
Erosion
Stasis


B
A
C
N
2 km
River Deben
KEY TO MAPS
Post-Red Crag Sediments
Holocene marine sediment
Holocene alluvium/tidal sediment
Holocene beach/dune sediment
Pleistocene alluvium (Kesgrave sbgp)
Red Crag Formation
Pre-Red Crag Sediments
Paleocene strata
Eocene strata
Present coastline
Coast movement (1991-2006)
D
Deposition
Erosion E
S Stasis
Potential sedimentation states on a sub-decadal scale
Dominant
Negligible
Red Crag Interval
(Stable Facies)
c. 2.7-2.4 Ma
Quaternary
(Multiple Facies Shifts)
c. 2.4 Ma - 1 ka
Present Day
(Stable Facies)
c. 1 ka -
SITE A (Red Crag at erosive outcrop)
SITE B (Red Crag at inland outcrop)
SITE C (No Red Crag at outcrop)
OR
(or D=E)


"NSC" limit
No Crag
Deposition
WC limit
NC limit
RC limit


A
B


A
B
C

LIST OF TABLES

Table 1 – Ichnofauna of the Red Crag Formation. Full description and ichnotaxonomic assignment of the trace fossils illustrated in Figure 3. Dimensions reported are the mean of examples observed in the study. Likely tracemakers are identified based upon information in Clifton & Thompson (1978), Humphreys & Balson (1988), Gingras et al. (2008a), Buatois et al. (2017), Knaust (2018). Abundance reports the approximate number of each ichnotaxon observed across all field locations visited during this study.

Ichnotaxon	Dimensions	Likely Tracemaker	Abundance	Description	Locations
Cylindrichnus isp.	W: 55 mm L: 225 mm	Polychaete	30	Concentrically lined burrow with conical aperture and heterolithic fill of sandstone, mudstone, and shell fragments.	BK, BM, WZ
Diopatrichnus isp.	W: 12 mm L: 100 mm	Annelid or Crustacean	15	Small sub-vertical burrow lined obliquely with shell fragments.	BK, CG, WZ
Macaronichnus segregatis	W: 3 mm L: 25 mm	Polychaete	> 100	Small, unbranched sub-vertical to sub-horizontal burrow with heterolithic infill. Occurs in dense patches, frequently cross-cutting.	BK, BM, SH, WZ
Polykladichnus irregularis	W: 13 mm L: 230 mm	Polychaete	30	Y-shaped burrow with a muddy infill. Often in association with *Skolithos*.	BM, CG, CH, NF
Psilonichnus upsilon	W: 60 mm	Crustacean	20	Large, occasionally branching sub-vertical burrow, with spiralling of	BM, WZ

	L: 1400 mm			the sediment laminae surrounding a fine core.	
Skolithos linearis	W: 12 mm L: 180 mm	Annelid or Crustacean	> 100	Unlined, unbranched vertical burrow, with a structureless muddy infill. Often in association with *Polykladichnus*.	BK, BM, CG, CH, NF, SH, WZ
Teichichnus rectus	W: 38 mm L: 47 mm	Annelid	5	Burrow with stacked arcuate spreite comprised of mudstone.	WZ
Thalassinoides isp.	W: 33 mm L: 700 mm	Crustacean	5	Complex burrow network with a mudstone infill.	WZ

Table 2 – Burrowing speeds of modern invertebrates (in cm^3 per hour).

		cm3/hr		
		Min	Max	
A	Bivalves	0.5	10	Gingras et al (2008)
B	Arthropods	0.2	2	Gingras et al (2008)
C	Echinoderms	0.05	5	Gingras et al (2008)
D	Polychaetes	0.01	0.5	Dafoe et al (2006)

Table 3 – Estimated time taken to construct selected burrows shown in Figure 3 – most likely tracemaker and burrowing rates refer to Table 2. Estimated times in excess of half a synodic tidal cycle are unlikely and shown in brackets.

Ichnotaxon	Figure	Approx. volume (cm3)	Most likely tracemaker	Maximum time estimate	Minimum time estimate
Diopatrichnus	3B	4.02	B	20 hours	2 hours
Macaronichnus	3D	0.06	D	6 hours	1 hour
Polykladichnus	3E	15.08	D	(1508 hours)	30 hours
Psilonichnus	3F	1382.3	B	(6911 hours)	138 hours